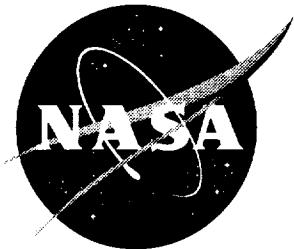


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# Fracture Tests on Thin Sheet 2024-T3 Aluminum Alloy for Specimens With and Without Anti-Buckling Guides

*William M. Johnston*  
*Analytical Services and Materials Inc., Hampton, Virginia*

National Aeronautics and  
Space Administration

Langley Research Center  
Hampton, Virginia 23681-2199

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# **Fracture Tests on Thin Sheet 2024-T3 Aluminum Alloy for Specimens with and without Anti-Buckling Guides**

William M. Johnston  
Analytical Services and Materials Inc.  
Hampton, Virginia

## **Abstract**

*A series of fracture test were conducted to determine the effects of specimen type, specimen width and buckling on the fracture behavior of cracked thin sheet (0.063 inch thick) 2024-T3 aluminum alloy. A summary of the experimental measurements is presented for fracture tests conducted on two specimen types and various widths. Middle-crack tension M(T) and compact tension C(T) specimens were tested in the L-T and T-L orientation with duplicate tests for each condition. Four widths (W= 3, 12, 24, and 40 inch) were tested for the middle-crack tension specimens, and three widths (W=2, 4, and 6 inch) were tested for the compact tension specimens. The M(T) specimens were tested in either a constrained (out-of-plane displacements restrained with anti-buckling guides) or unconstrained conditions were the specimen was free to buckle out of plane. Measurements were made of load against crack extension for all specimens.*

## **Introduction**

Thin sheet 2024-T3 aluminum alloy has been used in commercial aircraft fuselages for the past 50 years. As these commercial aircraft age, it is important to have fracture mechanics models developed to predict failure of the structure subjected to cracking scenarios such as multi-site-damage (MSD) and multi-element-damage (MED). When developing these methodologies it is important to first verify crack growth models on flat aluminum alloy sheets before addressing crack growth in the structure. These tests were designed to demonstrate the effects of specimen type, specimen width, and buckling on the fracture behavior of 0.063 inch thick 2024-T3. This set of fracture test results, along with the tensile stress strain properties, provide the information necessary for analysts to validate fracture mechanics residual strength methodology on this material.

The objective of this paper was to report the experimental measurements made on 0.063 inch thick 2024-T3 aluminum alloy fracture tests. The fracture behavior was characterized through a series fracture tests conducted on compact tension, C(T), and middle crack tension, M(T), specimens. The M(T) specimens were tested with and without anti-buckling guides to provide experimental data on the effects of crack buckling on fracture. The specimens were configured in both the L-T and T-L orientation. To minimize variation due to the material, all specimens were taken from the same lot of aluminum sheet. The test procedures are discussed and the experimental measurements of failure stress, load-against-crack-extension, and the material stress-strain curves are reported.

## **Experimental Procedure**

The fracture behavior of 0.063 inch thick 2024-T3 aluminum alloy was characterized through a series fracture tests on middle crack tension, M(T), and compact tension, C(T), specimens. The M(T) specimens were tested with and without anti-buckling guides to provide experimental data on the

where  $F$  is the applied load,  $W$  is width and  $B$  is thickness. The results for M(T) specimens with a L-T orientation are listed in Tables 12-20 and the results for the specimens with a T-L orientation are listed in Tables 21-25. The load-against-crack extension response of the two orientations is compared for the 3 inch M(T) specimens in Figures 10. The load-crack extension trends are compared for the constrained and unconstrained (buckling) M(T) specimens in Figures 11-16. The results from the 12 inch M(T) specimens for the L-T and T-L orientations are shown in Figures 10 and 11, respectively. The results from the 24 inch M(T) specimens for the L-T and T-L orientations are shown in Figures 13 and 14, respectively. Test Data from the 40-inch wide M(T) specimens is shown for both crack length to width ratios,  $2a/W = 1/5$  and  $2a/W = 1/3$  in figures 15 and 16 respectively.

### Tension Tests

The results from the tensile tests are presented in Figure 17. This figure shows the stress-strain results from the three tensile tests in each orientation along with a piecewise linear fit to the data. Tabulated values for both linear fits is shown in the two sets of data on Figure 17.

### Summary

Fracture and tensile tests were conducted on a thin sheet 2024-T3 aluminum alloy. Both middle crack tension M(T) and compact tension C(T) specimens were tested in the L-T and T-L orientation. Four widths ( $W= 3, 12, 24$ , and  $40$  inch) were tested for the middle crack tension specimens, and three widths ( $W=2, 4$ , and  $6$  inch) were tested for the compact tension specimens. The M(T) specimens were tested in an constrained (no out of plane displacement) and a unconstrained condition where the specimen was free to buckle out of plane. Results in the form of load-against-crack extension and stress-strain behavior were reported.

Table 4. Failure Stress for the M(T) TL Fracture Tests (B=0.063)

Width (inch)	M(T) TL constrained		M(T) TL unconstrained	
	Fail Stress (ksi)	Crack Length 2a (in)	Fail Stress (ksi)	Crack Length 2a (in)
3	33.2	.984	-	-
3	33.4	1.001	-	-
12	30.0	4.001	26.0	3.992
12	30.3	4.009	25.8	4.002
24	27.2	8.002	20.9	8.001
24	27.4	8.000	21.0	8.002

Table 5. Load and Crack Extension Measurements for 2 inch Wide C(T) LT Tests.

W=2in., a = 0.800		W=2in., a = 0.800		W=2in., a = 0.800	
Load (lbs)	$\Delta a$ (inch)	Load (lbs)	$\Delta a$ (inch)	Load (lbs)	$\Delta a$ (inch)
583	0.005	557	0.012	650	0.010
652	0.025	651	0.028	684	0.033
690	0.049	696	0.06	702	0.053
704	0.099	709	0.106	716	0.073
705	0.148	705	0.156	718	0.101
676	0.196	678	0.198	712	0.134
626	0.243	636	0.234	685	0.191
568	0.307	593	0.265	654	0.221
494	0.354	523	0.307	614	0.259
426	0.408	500	0.348	556	0.302
		449	0.396	502	0.350
				458	0.399
				395	0.430

Table 7. Load and Crack Extension Measurements for 6 inch Wide C(T) LT Tests.

W=6in.. a = 2.400 (a)		W=6in., a = 2.400		W=6in., a = 2.400	
Load (lbs)	$\Delta a$ (inch)	Load (lbs)	$\Delta a$ (inch)	Load (lbs)	$\Delta a$ (inch)
1073	0.016	1132	0.026	1001	0.008
1232	0.025	1389	0.068	1109	0.015
1492	0.029	1514	0.102	1198	0.024
1594	0.094	1602	0.142	1299	0.031
1693	0.128	1666	0.179	1399	0.056
1765	0.173	1694	0.222	1500	0.076
1826	0.224	1719	0.265	1601	0.123
1843	0.307	1734	0.317	1670	0.171
1803	0.315	1737	0.379	1704	0.220
1778	0.43	1722	0.439	1725	0.256
1750	0.497	1699	0.512	1732	0.303
1684	0.572	1655	0.587	1734	0.357
1642	0.648	1602	0.667	1735	0.406
1567	0.743	1552	0.745	1710	0.449
1494	0.826	1494	0.843	1691	0.491
1492	0.884	1327	0.934	1683	0.540
1372	0.964	1247	1.025	1618	0.601
1293	1.043	1182	1.096	1596	0.663
1227	1.119	1074	1.216	1553	0.715
1158	1.197	1013	1.279	1508	0.760
1090	1.284	932	1.320	1468	0.816
1012	1.368	866	1.405	1424	0.884
937	1.435	792	1.557	1354	0.973
868	1.514	729	1.634	1263	1.042
820	1.598	680	1.720	1206	1.112
756	1.656	618	1.802	1145	1.182
698	1.759	556	1.875	1079	1.248
				1030	1.309
				972	1.369
				919	1.464
				850	1.551

(a) surfaces developed V shear fracture

Table 9. Load and Crack Extension Measurements for 2 inch Wide C(T) TL Tests.

W=2in., a = 0.701		W=2in., a = 0.800		W=2in., a = 0.800	
Load (lbs)	$\Delta a$ (inch)	Load (lbs)	$\Delta a$ (inch)	Load (lbs)	$\Delta a$ (inch)
602	0.011	550	0.003	556	0.013
658	0.017	650	0.019	601	0.016
706	0.026	672	0.070	652	0.040
754	0.051	692	0.107	665	0.094
785	0.094	683	0.152	666	0.132
773	0.144	642	0.189	652	0.177
741	0.186	606	0.223	615	0.224
720	0.243	570	0.270	560	0.274
656	0.305	523	0.321	508	0.324
607	0.365	461	0.353	448	0.373
534	0.426	424	0.398	417	0.424
457	0.478	398	0.420		

Table 11. Load and Crack Extension Measurements for 6 inch Wide C(T) TL Tests.

W=6in.. a = 2.400		W=6in., a = 2.400		W=6in., a = 2.400	
Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)
945	0.011	801	0.002	902	0.004
1123	0.025	903	0.006	1003	0.007
1236	0.049	1001	0.010	1102	0.015
1395	0.098	1100	0.019	1200	0.027
1495	0.150	1195	0.036	1300	0.055
1547	0.209	1297	0.061	1397	0.100
1584	0.269	1399	0.099	1489	0.149
1600	0.325	1496	0.140	1569	0.198
1600	0.372	1548	0.183	1600	0.243
1587	0.441	1598	0.236	1613	0.287
1570	0.518	1625	0.400	1626	0.336
1550	0.572	1626	0.438	1623	0.401
1512	0.658	1615	0.467	1601	0.449
1445	0.722	1576	0.552	1573	0.513
1399	0.797	1547	0.604	1541	0.574
1336	0.875	1492	0.682	1509	0.644
1278	0.949	1466	0.731	1470	0.698
1221	1.015	1418	0.794	1420	0.748
1156	1.072	1351	0.856	1388	0.814
1115	1.149	1299	0.943	1332	0.866
1060	1.226	1246	1.010	1291	0.926
1000	1.295	1195	1.109	1243	0.995
934	1.35	1115	1.175	1189	1.114
893	1.421	1066	1.239		
836	1.491	1018	1.296		
770	1.550	975	1.382		
729	1.629	898	1.473		
681	1.692	829	1.546		
650	1.774	770	1.606		
		699	1.745		
		629	1.797		
		593	1.858		
		555	1.922		
		515	1.994		

Table 13. Load and Crack Extension Measurements for 12 inch Wide M(T) LT Tests.

W=12in., constrained 2a = 4.000			W=12in., constrained 2a = 4.160		
Load (kips)	Δa (inch)	Δa (inch)	Load (kips)	Δa (inch)	Δa (inch)
11.04	0.007	0.005	11.00	0.003	0.005
12.02	0.009	0.008	12.00	0.006	0.009
13.01	0.012	0.010	13.00	0.009	0.013
14.03	0.014	0.013	14.02	0.012	0.015
15.01	0.020	0.016	15.02	0.016	0.023
16.01	0.029	0.023	16.01	0.021	0.029
17.03	0.033	0.030	17.02	0.042	0.040
18.03	0.055	0.049	18.02	0.055	0.054
19.01	0.070	0.059	19.02	0.071	0.071
20.01	0.089	0.080	20.03	0.087	0.094
21.03	0.111	0.104	21.02	0.116	0.118
22.01	0.152	0.124	22.02	0.152	0.151
23.02	0.170	0.156	22.51	0.179	0.175
23.93	0.222	0.212	23.02	0.209	0.207
24.44	0.275	0.271	23.48	0.266	0.257
24.64	0.333	0.325	23.69	0.310	0.304
24.74	0.419	0.398	23.80	0.357	0.359
24.61	0.475	0.460	23.81	0.405	0.396
24.37	0.561	0.532	23.80	0.453	0.455
24.01	0.65	0.594	23.61	0.500	0.506
23.62	0.735	0.701	23.43	0.576	0.601
23.13	0.803	0.755	23.07	0.640	0.660
22.77	0.925	0.887	22.73	0.683	0.706
21.97	1.020	0.955	22.54	0.758	0.762
21.59	1.173	1.114	22.15	0.865	0.903
20.44	1.296	1.190	21.42	0.950	1.027
19.94	1.343	1.305	20.78	1.623	1.142
19.38	1.631	1.395	20.13	1.192	1.202
18.15	1.686	1.740	19.44	1.285	1.343
16.65	1.993	1.828	18.70	1.496	1.450
			17.63	1.559	1.606
			16.90	1.766	1.657

Table 15. Load and Crack Extension Measurements for 12 inch Wide M(T) LT Tests.

W=12in., unconstrained 2a = 4.004			W=12in., unconstrained 2a = 4.004		
Load (kips)	$\Delta a$ (inch)	$\Delta a$ (inch)	Load (kips)	$\Delta a$ (inch)	$\Delta a$ (inch)
12.00	0.009	0.002	10.02	0.003	0.001
13.01	0.012	0.005	11.02	0.008	0.008
14.00	0.018	0.010	12.02	0.017	0.014
15.03	0.025	0.022	13.01	0.023	0.022
16.01	0.043	0.038	14.03	0.028	0.026
17.02	0.070	0.067	15.02	0.039	0.034
18.01	0.083	0.083	16.03	0.052	0.063
19.01	0.121	0.111	17.01	0.080	0.072
19.51	0.132	0.134	18.01	0.100	0.093
20.00	0.181	0.164	19.01	0.135	0.121
20.51	0.237	0.215	20.03	0.197	0.186
20.68	0.270	0.257	20.57	0.252	0.241
20.80	0.316	0.294	20.76	0.312	0.301
20.86	0.360	0.343	20.89	0.401	0.362
20.86	0.401	0.406	20.93	0.460	0.423
20.74	0.467	0.467	20.77	0.528	0.528
20.57	0.555	0.542	20.62	0.608	0.561
20.25	0.588	0.577	20.32	0.602	0.602
20.18	0.647	0.646	20.19	0.700	0.621
19.85	0.759	0.783	20.10	0.756	0.721
19.23	0.801	0.831	19.53	0.883	0.822
19.04	0.852	0.869	19.04	1.022	0.964
18.76	0.942	0.929	18.22	1.225	1.145
18.38	1.167	1.129	17.14	1.359	1.251
17.10	1.206	1.169	16.44	1.883	1.454
16.97	1.486	1.400	14.87	1.923	1.803
15.41	1.947	1.589	13.18	2.113	2.113
15.42	1.968	1.689	10.90	2.437	2.437
13.16	2.380	1.893			

Table 17. Load and Crack Extension Measurements for 24 inch Wide M(T) LT Tests.

W=24in., unconstrained 2a = 8.022			W=24 in., unconstrained 2a = 7.999		
Load (kips)	$\Delta a$ (inch)	$\Delta a$ (inch)	Load (kips)	$\Delta a$ (inch)	$\Delta a$ (inch)
15.02	0.003	0.008	15.00	0.006	0.007
16.00	0.005	0.009	16.00	0.009	0.009
17.00	0.008	0.012	17.02	0.012	0.013
18.02	0.016	0.020	18.04	0.018	0.018
19.02	0.018	0.023	19.00	0.023	0.020
20.00	0.025	0.035	20.04	0.003	0.027
21.00	0.031	0.044	21.02	0.037	0.034
22.02	0.040	0.054	22.02	0.047	0.045
23.02	0.054	0.069	23.00	0.057	0.051
24.00	0.070	0.083	24.04	0.065	0.067
25.04	0.086	0.098	25.02	0.081	0.080
26.02	0.107	0.123	26.04	0.096	0.093
27.00	0.133	0.147	27.08	0.121	0.113
28.00	0.156	0.176	27.98	0.144	0.138
29.00	0.198	0.216	29.00	0.170	0.165
29.52	0.216	0.242	30.04	0.205	0.218
30.00	0.251	0.279	30.62	0.234	0.240
30.52	0.293	0.316	31.48	0.281	0.299
31.00	0.340	0.376	32.10	0.345	0.344
31.36	0.394	0.427	32.36	0.379	0.383
31.48	0.431	0.500	32.58	0.438	0.447
31.70	0.483	0.567	32.80	0.477	0.491
32.00	0.558	0.649	33.02	0.549	0.549
32.06	0.581	0.693	33.20	0.584	0.589
32.08	0.664	0.770	33.30	0.659	0.660
32.22	0.812	0.924	33.28	0.724	0.721
31.90	0.830	0.967	33.32	0.777	0.776
31.92	0.884	1.005	33.20	0.824	0.835
31.94	1.017	1.155	33.34	0.871	0.880
31.50	1.108	1.245	33.18	1.053	1.132
31.24	1.148	1.316	32.76	1.400	1.397
31.22	1.317	1.528	31.92	1.767	1.730
			30.64	2.087	2.014
			29.40	2.112	2.106
			29.10	2.458	2.415
			27.72	2.542	2.518
			27.56	2.918	2.812
			25.90	2.972	2.853
			25.90	2.972	2.853

Table 19. Load and Crack Extension Measurements for 40 inch Wide M(T) LT Tests.

W=40in., unconstrained 2a=13.333			W=40in., constrained 2a = 8.004		
Load (kips)	$\Delta a$ (inch)	$\Delta a$ (inch)	Load (kips)	$\Delta a$ (inch)	$\Delta a$ (inch)
23.02	0.012	0.007	29.98	0.001	0.001
24.00	0.020	0.011	35.00	0.004	0.006
25.02	0.025	0.019	40.02	0.012	0.008
26.02	0.027	0.021	44.98	0.002	0.030
22.10	0.035	0.033	50.02	0.047	0.056
28.02	0.038	0.053	55.00	0.084	0.084
29.18	0.051	0.035	60.00	0.122	0.123
30.02	0.061	0.062	65.00	0.176	0.173
31.02	0.074	0.073	70.00	0.249	0.247
32.00	0.086	0.091	75.00	0.366	0.348
33.00	0.095	0.106	80.02	0.530	0.527
34.00	0.109	0.130	82.50	0.654	0.659
35.00	0.140	0.152	85.00	0.837	0.832
36.00	0.165	0.175	86.72	1.259	1.024
37.00	0.200	0.204	87.72	1.259	1.267
38.00	0.226	0.240	88.32	1.439	1.377
39.00	0.272	0.285	88.72	1.648	1.600
39.64	0.313	0.350	88.70	-	1.793
40.02	0.333	0.349	88.78	-	1.199
40.70	0.400	0.393	88.30	-	2.297
41.20	0.446	0.446	87.62	-	2.569
41.66	0.491	0.486	86.72	-	2.855
41.98	0.524	0.524	85.52	-	3.040
42.38	0.588	0.574	81.72	-	3.318
42.80	0.641	0.639			
43.12	0.703	0.690			
43.32	0.723	0.744			
43.64	0.763	0.805			
43.84	0.831	0.869			
44.10	0.887	0.927			
44.28	0.934	1.002			
44.44	1.024	1.117			
44.42	1.304	1.292			
44.42	1.436	1.448			
44.12	1.651	1.752			
44.06	1.908	1.948			
43.20	3.158	2.602			

Table 21. Load and Crack Extension Measurements for 3 inch Wide M(T) TL Tests.

W=3in., constrained 2a = .984		W=3in., constrained 2a = 1.001	
Load (lbs)	2a (inch)	Load (lbs)	2a (inch)
518	0.984	3990	1.001
1510	0.986	4490	1.003
2005	0.989	5000	1.007
2510	0.989	5490	1.016
3607	0.989	6000	1.044
6207	1.105	6230	1.144
6314	1.237	6270	1.195
5986	1.299	6130	1.262
5802	1.416	6060	1.341
4953	1.604	5910	1.410
4847	1.695	5740	1.460
4470	1.831	5550	1.564
		5240	1.624
		5080	1.698
		4770	1.799
		4490	1.871
		4250	2.019
		3710	2.140

Table 23. Load and Crack Extension Measurements for 12 inch Wide M(T) TL Tests.

W=12in., unconstrained 2a = 3.992		W=12in., unconstrained 2a = 4.002	
Load (kips)	2a (inch)	Load (kips)	2a (inch)
12.01	3.999	12.03	4.01
13.01	4.012	14.02	4.028
14.00	4.018	16.02	4.073
15.01	4.031	17.01	4.125
16.01	4.070	18.01	4.229
17.01	4.140	18.30	4.280
17.53	4.185	18.77	4.338
18.02	4.244	19.01	4.409
18.53	4.302	19.23	4.492
19.02	4.386	19.36	4.568
19.51	4.531	19.44	4.657
19.64	4.698	19.48	4.748
19.64	4.853	19.43	4.832
19.54	5.193	19.43	4.956
19.03	5.595	18.75	5.233
18.05	6.105	18.86	5.373
16.83	6.846	18.54	5.492
14.72	7.597	18.30	5.713
		17.79	5.809
		17.51	6.330
		16.15	7.113
		13.95	7.624
		12.50	8.482

Table 25. Load and Crack Extension Measurements for 24 inch Wide M(T) TL Tests.

W=24in., unconstrained 2a = 8.001			W=24in., unconstrained 2a = 8.002		
Load (kips)	$\Delta a$ (inch)	$\Delta a$ (inch)	Load (kips)	$\Delta a$ (inch)	$\Delta a$ (inch)
16.02	0.006	0.007	16.36	0.006	0.004
18.02	0.014	0.011	17.20	0.008	0.007
20.06	0.029	0.024	18.84	0.011	0.018
21.02	0.038	0.037	20.06	0.021	0.015
22.05	0.066	0.065	21.02	0.031	0.018
24.14	0.087	0.091	22.00	0.037	0.038
25.56	0.115	0.127	23.04	0.050	0.067
26.32	0.130	0.160	24.02	0.066	0.094
27.36	0.169	0.186	25.02	0.094	0.110
27.92	0.205	0.216	26.04	0.131	0.151
28.62	0.235	0.249	27.04	0.158	0.188
29.16	0.278	0.290	28.00	0.194	0.233
29.56	0.314	0.318	28.92	0.249	0.281
30.26	0.425	0.389	29.44	0.308	0.334
30.70	0.465	0.432	29.96	0.355	0.396
30.95	0.524	0.479	30.42	0.425	0.442
31.18	0.575	0.544	30.76	0.450	0.495
31.22	0.642	0.582	31.12	0.488	0.543
31.34	0.673	0.647	31.32	0.564	0.607
31.47	0.773	0.719	31.50	0.633	0.674
31.40	0.815	0.777	31.62	0.716	0.788
31.42	0.848	0.840	31.64	0.748	0.832
31.54	1.016	0.938	31.68	0.841	0.904
31.12	1.034	1.085	31.62	0.948	1.012
30.30	2.435	2.472	31.50	1.042	1.099
26.80	2.758	2.530	31.34	1.320	1.341
22.92	3.631	3.305	31.12	1.441	1.502
			30.62	1.598	1.699
			30.14	1.653	1.822
			29.74	1.848	2.046
			28.98	1.923	2.126
			28.66	2.219	2.553
			27.40	2.599	2.675
			26.46	2.627	3.259
			25.22	2.654	2.938

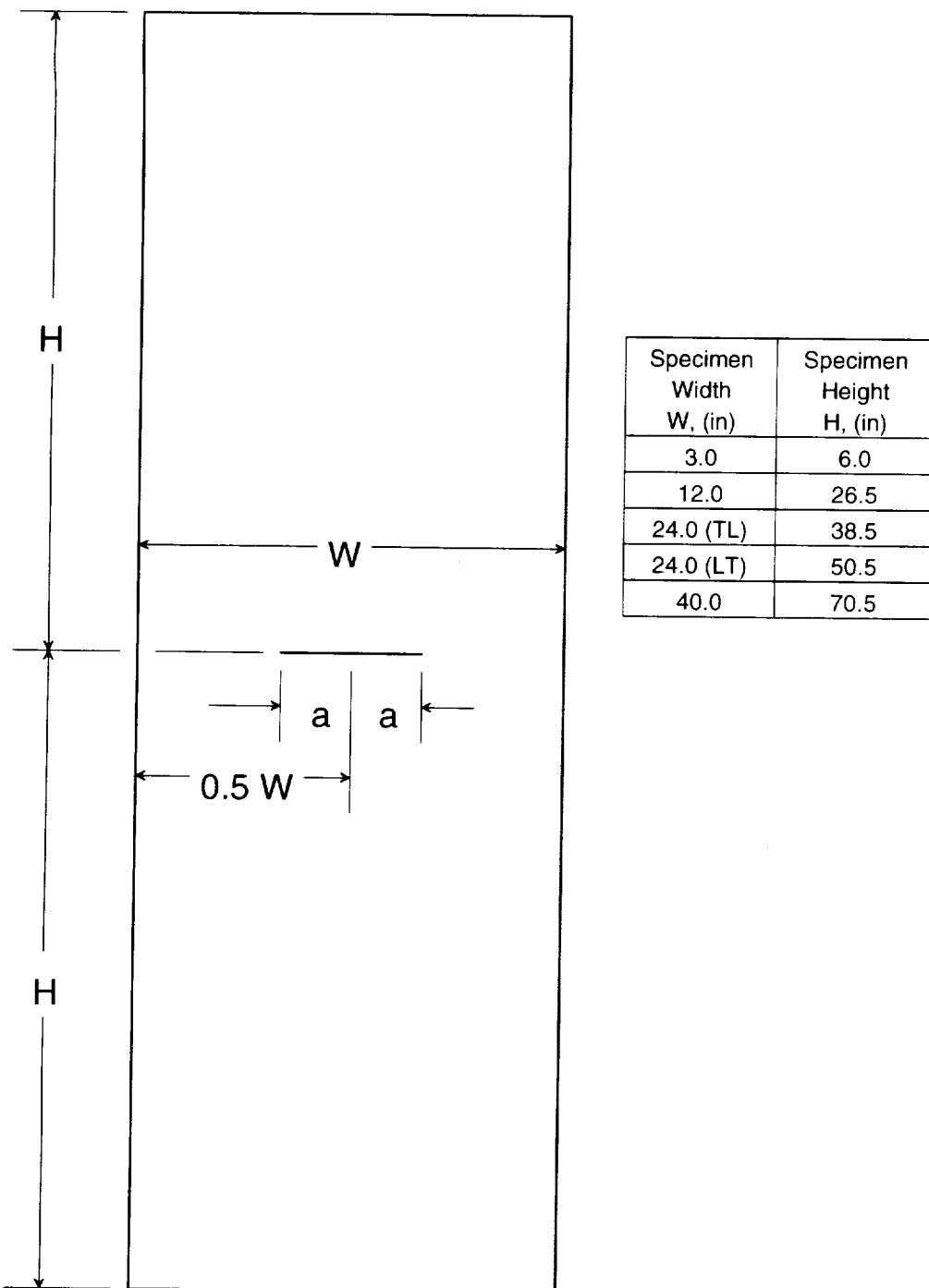


Figure 2. Schematic of a middle tension specimen ( $W$  = specimen width).

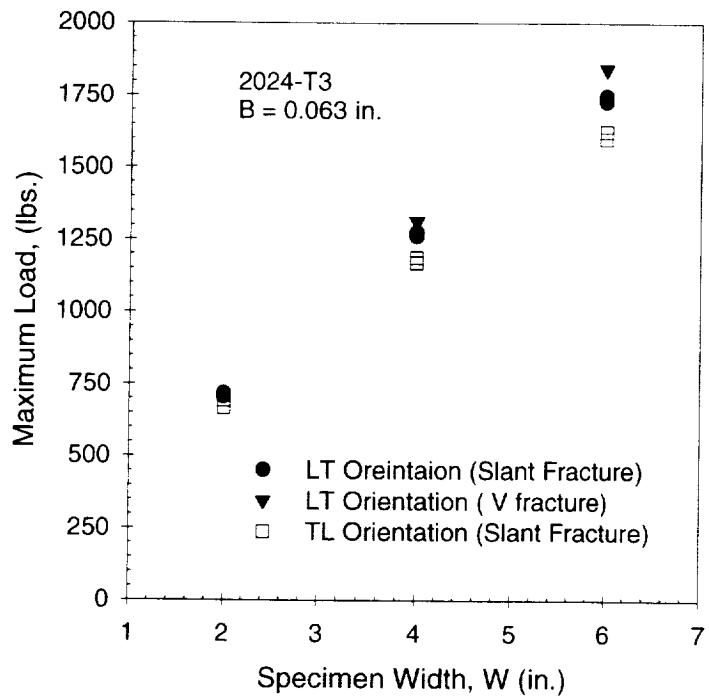


Figure 5. Failure loads for C(T) specimens of different widths.

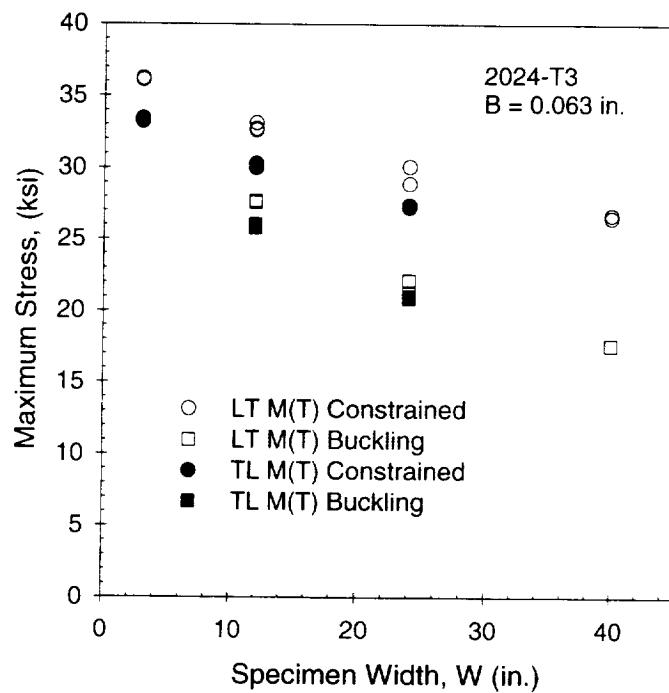


Figure 6. Failure stress results for M(T) specimens of different widths.

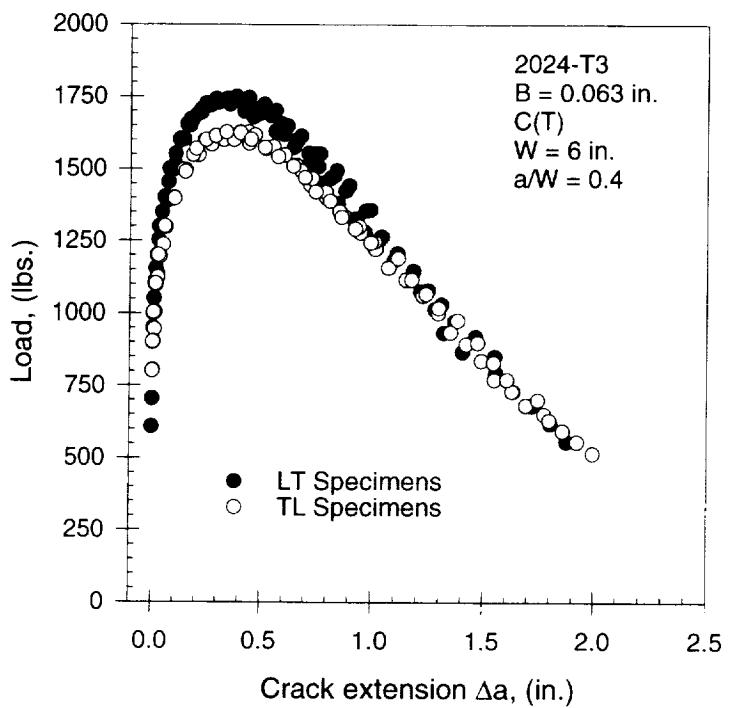


Figure 9. Load against crack extension results for the 6-inch-wide C(T) specimen.

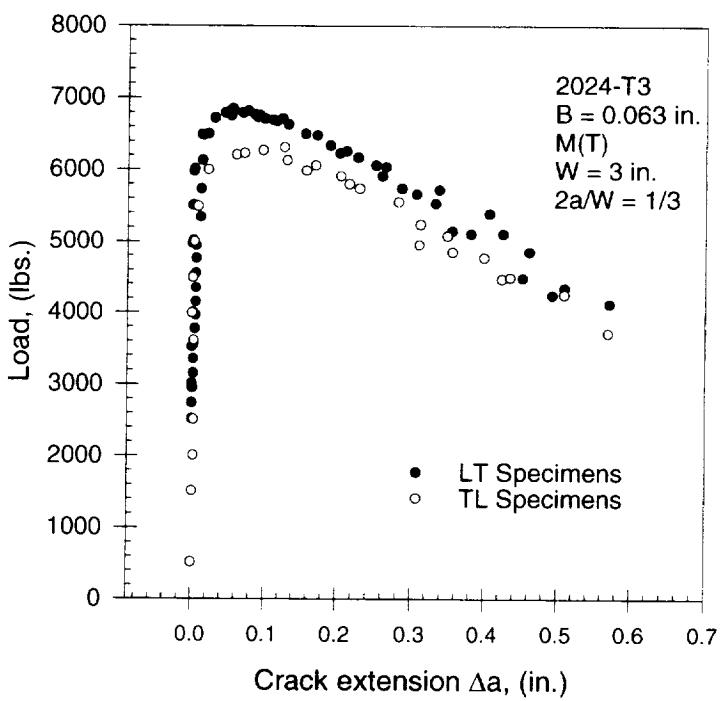


Figure 10. Load against crack extension results for the 3-inch-wide M(T) specimen.

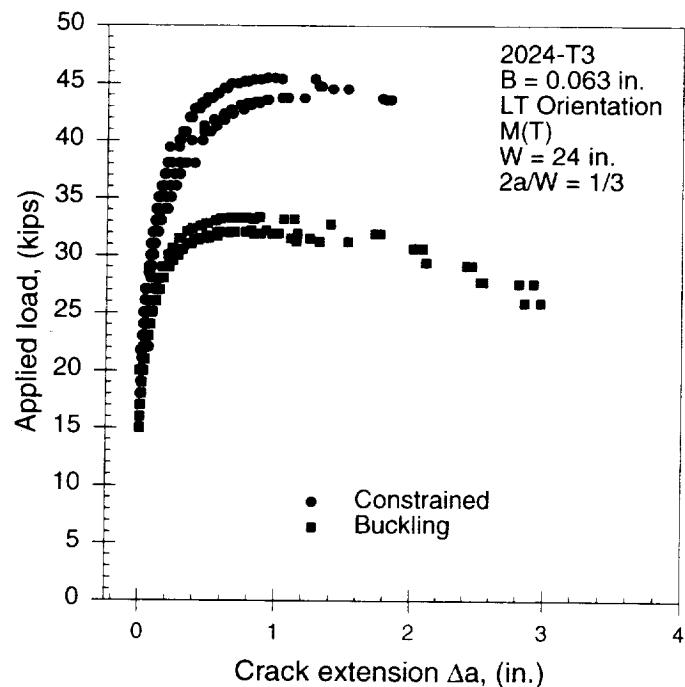


Figure 13. Buckling and constrained applied load against crack extension results for LT orientation 24-inch-wide M(T) specimens.

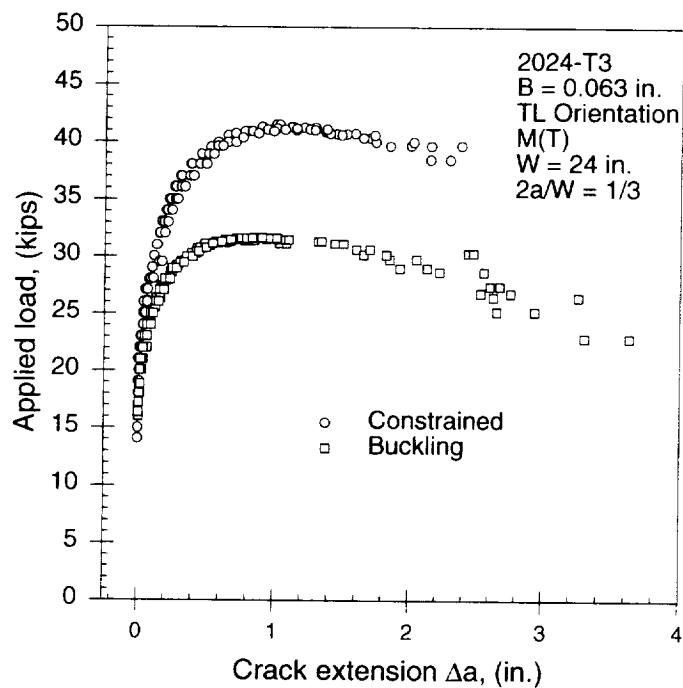


Figure 14. Buckling and constrained applied load against crack extension results for TL orientation 24-inch-wide M(T) specimens.

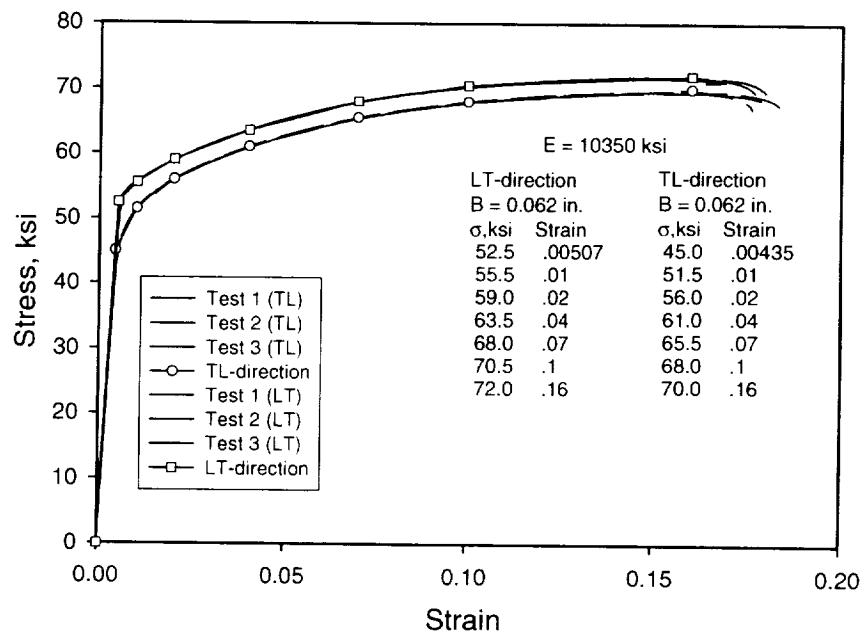


Figure 17. Tensile results for 2024-T3 aluminum alloy results.